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Asymmetric Epoxidation of Enones Promoted by Dinuclear Magnesium Catalyst

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Abstract: Asymmetric synthesis with cheaper and non-toxic alkaline earth metal catalysts is becoming an important and sustainable alternative to conventional catalytic methodologies mostly relying on precious metals. In spite of some sustainable methods for enantioselective epoxidation of enones, the development of a well-defined and efficient catalyst based on magnesium complexes for these reactions is still a challenging task. In this perspective, we present the application of chiral dinuclear magnesium complexes for asymmetric epoxidation of a broad range of electron-deficient enones. We demonstrate that the in situ generated magnesium-ProPhenol complex affords enantioenriched oxiranes in high yields and with excellent enantioselectivities (up to 99% ee). Our extensive study verifies the literature data in this area and provides a step forward to better understand the factors controlling the oxygenation process. Elaborated catalyst offers mild reaction conditions and a truly wide substrate scope.

Keywords: asymmetric epoxidation; magnesium; enones; ProPhenol; TBHP

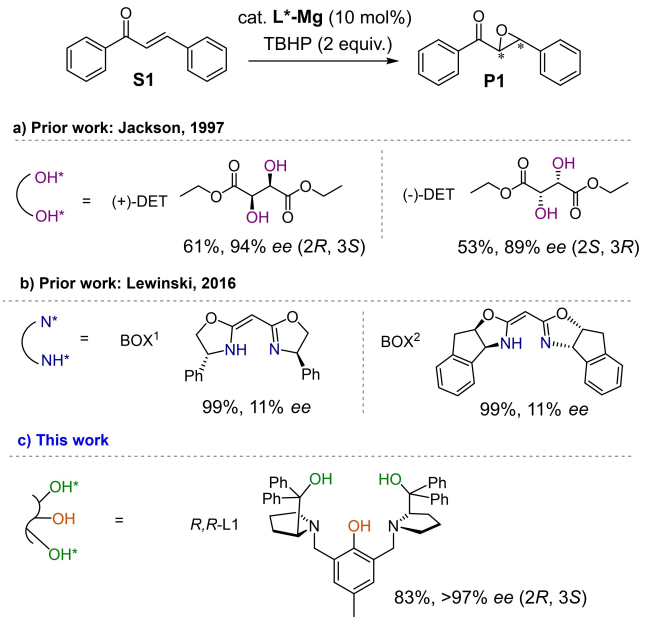
Introduction

A fundamental discovery done by Sharpless over 40[1] years ago regarding the possibility of asymmetric epoxidation of allyl alcohols with a chiral titanium complex significantly prompted the practical application of epoxides in the asymmetric synthesis. Optically pure oxirane derivatives can be further transformed into various more refined enantiomerically pure intermediates[2] or target molecules,[3] particularly natural products,[4] pharmaceuticals[5] or drug candidates.[6] This discovery, inspired a tremendous development of new strategies in the field of asymmetric epoxidation, not only restricted to metal catalysis,[7] but also application of organocatalysts,[8] bioinspired transformations[9] and recently in the light-mediated processes.[10] This resulted also in significant enlarging the range of substrates used from simple alkenes[11] to complex molecules that are functionalized at the last stage of synthesis.[12]

Despite the enormous progress made in the development of new methodologies for stereocontrolled epoxidation of α,β-unsaturated carbonyl compounds, the topic still seems to be relevant, and most research is moving toward the discovery of more sustainable catalysts and reaction conditions nowadays. Particularly interesting seems to be the application of nontoxic alkaline metals being demanded for the production of active pharmaceutical ingredients (API).

Magnesium driven transformations such as cycloaddition,[13] domino,[14] ring opening,[15] Michael addition reactions[16] are just simply examples unrevealing the wide application of this metal in synthesis.[17] Magnesium complex offers also milder Lewis acidity compared to traditional transition metals. This made magnesium peroxide very promising catalysts for the epoxidation of electron-deficient olefins.

In 1997, Jackson and co-workers presented the formation of optically pure epoxides from chalcones by using a chiral magnesium complex with both enantiomers of ethyl tartarate (Scheme 1., 1a).[18] Conversion of the corresponding *E*-chalcones to epoxy derivatives was reported with 81–94% *ee* and with moderate yields 36–61% while the investigation were limited to only 5



Scheme 1. Development of methods of asymmetric epoxidation of *E*-chalcone **S1** using chiral magnesium complexes.

examples. After 4 years, the same group published the results of epoxidation of aliphatic enones. Initially, epoxides have been formed with 40–54% yields and 67–82% *ee* by using 25% of the chiral complex Mg-(+)-DET and TBHP as an oxidant.[19]

During further studies, the conditions were improved by replacing (+)-DET chiral ligand with its tert-butyl derivative, which resulted in improvement both reaction yield (92–96%) and enantioselectivity (91–93% *ee*) by using 10 mol% of the catalyst. Although the tested substrate scope was narrow, it was shown that the epoxidation of 3-octen-2-one with the addition of molecular sieves and 1 equiv. of water or with aqueous TBHP, the product was obtained with 99–100% substrate conversion and the *ee* was increased to 97% with a reduction of the amount of catalyst to 6 mol%.[20] Besides, they examined addition of ethanol instead of water in the epoxidation and found that the amount of 0.48 equiv. EtOH affected the reaction results (conversion 94–99%, 91–96% *ee*). Interestingly, despite decades of extensive studies on the reactivity of zinc- and magnesium alkyls towards O_2,[21,22] the isolation and structural characterization of well-defined magnesium complexes still remained a challenge at that time.

After 10 years of Jackson's research, Lewinski revised the topic of magnesium-promoted asymmetric epoxidation of *E*-chalcone **S1** with closer insight into the structures of magnesium alkyl peroxides based on β-diketiminate ligands (Scheme 1., 1b).[21] Lewinski revealed also that the structures proposed by Jackson are not correct and showed evidence of the formation of Mg-based mononuclear alkoxide species as well as its dimerization to the stable alkylperoxides where each oxygen coordinate to two Mg atoms.[21] However, despite specifying the correct catalyst structure, the problem of enantioselectivity was not correctly addressed. The epoxidation carried out in the stoichiometric variant as well as in the catalytic variant (10 mol% of the catalyst) resulted in the formation of a product with quantitative yield in a short time but with only low *ee* around 11%.

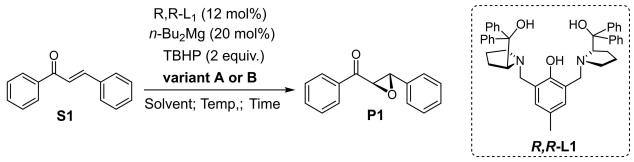
These research and insight into the correct structure of magnesium complexes[23] prompted us to verify the hypothesis of Jackson's group and ultimately to design magnesium-based highly enantioselective catalysts for asymmetric epoxidation of a broad range of *α,β*-unsaturated carbonyl compounds. Our idea was to put two magnesium atoms in one catalyst molecule to facilitate the formation of structures in which oxygen atoms coordinate simultaneously to two metal centers. In this paper, we show that the application of chiral dinuclear magnesium catalyst based on the C_2-symmetry *R,R*-ProPhenol ligand performs better than previously published protocols in terms of enantioselectivity, while providing good to high reaction yields (Scheme 1., 1c).

Results and Discussion

Bearing in mind the divergent conclusions published by the two research groups, we decided to address this important topic thoroughly. To verify the hypothesis of our both predecessors, we began by repeating the *E*-chalcone **S1** epoxidation by using the procedure from 1997. After many attempts, as well as modifications to the original procedure, the results described by this group (Table 1, Supporting Information) could not be fully reproduced and the tested complexes turned out to be capricious catalysts, unfortunately. Based on subsequent work, we assumed that the DET ligands does not offer a stable structure with two magnesium atoms, which can lead to oxidation in many ways, hence the repeatability of the reaction leaves much to be desired.

Bearing in mind the formation of the dimeric structure of magnesium alkoxide in this process, we chose ligands enabling the construction of such an architecture with two magnesium centers in one catalyst molecule. After many trials, we found that C_2-symmetry Mg-*R,R*-ProPhenol (***R,R*-L1**) complex seems to be the catalyst of choice for asymmetric epoxidation of the basic *E*-chalcone **S1**. To compare the results by using both catalysts, two experiments were carried out parallelly (Table 4, Supporting information). Initially, we performed comparative experiments on the epoxidation of S1 with Mg-(*R,R*)-ProPhenol catalyst according to both Jackson's and Lewinski's protocols. It quickly turned out that

Table 1. Screening of solvents and temperature optimization in the enantioselective epoxidation of *E*-chalcone S1 under variant A (without catalyst oxygenation) and variant B (with catalyst oxygenation).



Entry/Variant[b]	Solvent	Temp. [°C]	Time [h]	Yield[h] [%]	*ee*[i] [%] (2*R*,3*S*)
1/A	Toluene	0 to 10	24	60	69
2[c]/B		0 to 10	24	79	79
3[d]/B		0	96	79	91
4/A	Et_2O	0 to 10	24	35	37
5/B		0 to 10	24	83	78
6/B		0	144	80	81
7/A	MTBE	0 to 10	24	88	86
8/B		0 to 10	24	83	85
9/B	DME	0	144	18	86
10/B	THF	0 to 10	24	30	92
11[e]/B	1,4-dioxane	10 to 13	24	55	88
12/B	DCM	0 to 10	24	73	19
13/B	ACN	0 to 10	24	76	85
14/B	Toluene/ACN (1:1)	0	144	70	90
15[f]/B	Toluene/MTBE (1:1)	0	20	93	78
16/B	Toluene/DME (1:1)	0	144	61	84
17/B	Toluene/Et_2O (1:1)	0	144	88	84
18[g]/B	Toluene/1,4-dioxane (1:1)	0	144	94	90
19[g]/B	Toluene/1,4-dioxane (1:9)	0	96	74	93
20[f]/B	Toluene/THF (1:1)	0	56	95	87
21[f]/B	Toluene/THF (9:1)	0	20	94	72
22/B	**Toluene/THF (1:9)**	**0**	**96**	**78**	**96**
23/B		5	72	81	92
24/B		25	72	88	83

[a] Reactions were carried out by stirring the ligand 12 mol% *R,R*-L1 with 20 mol% *n*-Bu_2Mg (0.5 M solution in *n*-heptane) in solvent (1.84 mL) at room temperature for 1 h containing 2 eq. (0.8 mmol) of TBHP (4.0 M toluene solution), 1 eq. of chalcone **S1** (0.4 mmol) dissolved in 2.0 mL of appropriate solvent or its mixture unless otherwise stated.

[b] **Variant A** – After synthesis of the chiral complex Mg-*R,R*-L1, the solution is cooled to −10 °C. Then 2 eq. (0.8 mmol) of TBHP (4.0 M toluene solution) followed by 2.0 mL of chalcone **S1** solution were added in one portion. The mixture is warmed to 0 °C and stirring is continued for the specified time; **Variant B** – After the synthesis of the chiral complex Mg-*R,R*-L1, the solution is cooled to −20 °C and the Schlenk vessel is connected to the line with a desiccant and further to the oxygen balloon. Oxygen is supplied for 1 hour at 625 rpm. Then 2 eq. (0.8 mmol) of TBHP (4.0 M toluene solution) followed by 2.0 mL of chalcone **S1** solution were added in one portion. The mixture is warmed to a dedicated temperature and stirring is continued for the specified time.

[c] Reactions were carried out with 10 mol% *R,R*-L1 and 10 mol% *n*-Bu_2Mg (0.5 M solution in *n*-heptane).

[d] 0.8 eq. EtOH was added after chiral complex Mg-*R,R*-L1 synthesis and additionally stirred for 30 min.

[e] O_2 delivering at 10 °C.

[f] Complete **S1** conversion.

[g] O_2 delivering at 5 °C.

[h] Isolated yield after silica gel chromatography.

[i] Determined by chiral HPLC analysis.

Lewinski's conclusions were correct and this reaction protocol ensured higher enantiomeric excesses. It is important to emphasize that Lewinski's thorough research concerning the formation of an active magnesium complex and the oxygenation of alkyl magnesium species are crucial for the course of the reaction and greatly influenced our investigation.

First, we attempted to careful optimization of the reaction conditions. Initial experiments have been carried out for chalcone **S1** with TBHP in various solvents under the two protocols described in Table 1. **Variant A** (Table 1) assumed conducting epoxidation without catalyst oxygenation before TBHP and S1 addition to the reaction mixture, while **Variant B**

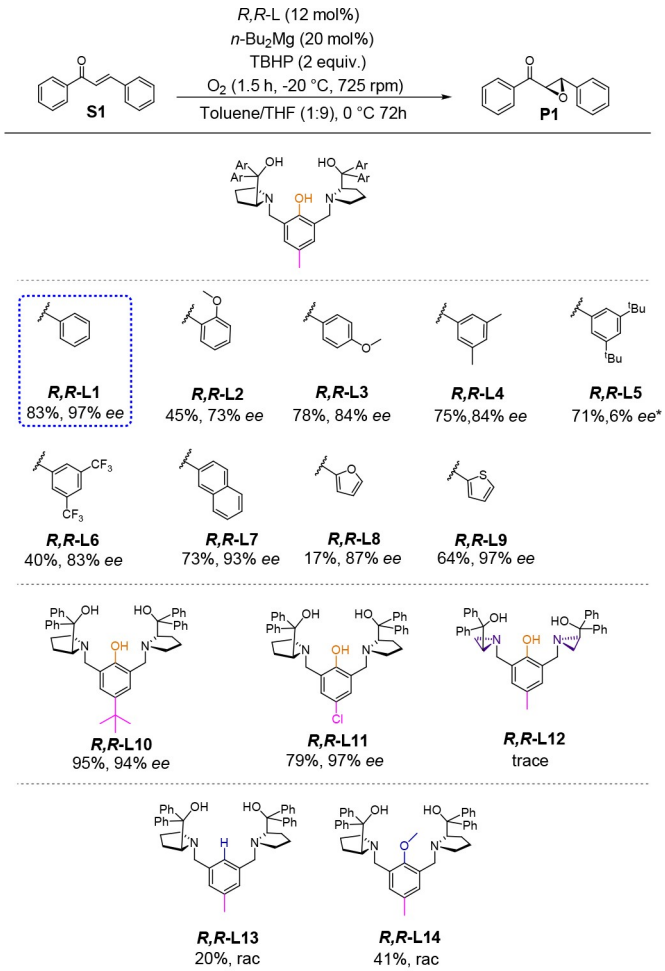
(Table 1) assumed supplying oxygen to the catalyst for 1 hour at −20 °C before adding other reagents to the reaction mixture. Conducting differential experiments confirmed our earlier observations that oxygenation of the catalyst solution is crucial for obtaining high reaction yields and high asymmetric induction.

The initial studies towards the development of efficient conditions began with the evaluation of various solvents (Table 1). With ***R,R*-L1**, as a ligand in toluene at 0 °C, the transformation reached completion within 96 h, affording the chiral epoxide **P1** with high enantioselectivity (entry 3). High level of enantioselectivity (85%) and good yield have been also maintained in MTBE (entry 8) while the reaction carried out in THF was highly enantioselective yet not efficient (entry 10). However, the best results in terms of enantioselective formation of epoxide **P1** (96% *ee*) were recorded in the toluene/THF (1:9) mixture (Table 1, Entry 22). Prolonged reaction time (96 h) at 0 °C resulted in the formation of **P1** with 78% yield. Slightly lower enantioselectivities (91–93% *ee*) and similar 74% yields were observed for toluene/1,4-dioxane mixture (Table 1, entry 19). Notably, decreasing the temperature to −20 °C had a negative effect on the epoxidation process. The product **P1** was isolated with only 26% yield, while providing lower enantioselectivities up to 52% *ee*. We also carried out experiments with different oxidizing agents like cumyl hydrperoxide (CHP), H_2O_2 (30%, aq.) and oxygen (Table 6, Supporting Information). In case of CHP we obtained product **P1** with 21% yields and 44% *ee*, while using hydrogen peroxide (30% aq.) was not promising due to water contamination that resulted in the catalyst decomposition. Also, the use of oxygen, without any other oxidants did not cause the epoxide formation. After this careful analysis, the reaction carried out in toluene/THF mixture (1:9) at 0 °C has been selected for further stages of research.

Concerning the reaction protocol, the optimal scenario assumed the oxygenation of the 2.0 mL volume of the catalyst *n*-BuMg-*R,R*-L1 and the addition of **S1** in a solution which would also be confirmed in the previous optimization studies related to the selection of the solvent. Detailed optimisation is collected in Supporting Information material (Table 7). Finally, we investigated the influence of Mg/***R,R*-L1** molar ratio on the reaction enantioselectivity. Results ultimately proved that the assumed metal-to-ligand structures (2:1) build up the most efficient and enantioselective catalysts. The slight excess of ***R,R*-L1** used in relation was beneficial for longer (72 h) epoxidation and reduced the influence of slow degradation of ProPhenol ligand. The addition of chalcone **S1** in solution instead of the solid substrate proved also to be optimal.

After confirming the effectiveness of ***R,R*-L1** ligand in asymmetric epoxidation, we also checked carefully the influence of the ligand tuning on the reaction enantioselectivity. Knowing that the optimal reaction parameters are crucial for enantioselectivity, we left this step unconventionally at the end to verify all ligands under the best conditions.

Scheme 2 summarizes comparison of results obtained for various chiral ProPhenol ligands (***R,R*-L2**–***R,R*-L14**). The data collected during these experiments indicate that a slight change in the structure of the ***R,R*-L** ligand had a significant influence on the enantioselectivity and yield of the reaction. Evolution of the ligands with substituents on the aryl ring showed that any substituents decrease enantioselectivity, regardless of their electronic nature. This effect was most evident for the bulky tert-butyl substituents in ***R,R*-L5**. Interestingly, high enantioselectivity of 97% *ee* was maintained for the ligand ***R,R*-L9** with the 2-



[a] Reaction conditions: *n*-Bu_2Mg (0.5 M solution in *n*-heptane), TBHP (4.0 M Toluene solution), 1 eq. of chalcone **S1** (0.4 mmol) dissolved in 2.0 mL Toluene/THF (1:9). Yields of isolated epoxides after silica gel chromatography. *Absolute configuration obtained enantiomer was (2*S*, 3*R*)

Scheme 2. Structures of tested *R,R*-L-ProPhenol ligands.

thiophenyl group. These studies have also shown that the coordination of magnesium to phenolic -OH is essential for high catalyst efficiency and enantioselectivity. Thus, ligands ***R,R*-13**, and **14** turned out inefficient. However, the para-substitution of the phenol ring did not change the catalyst efficiency significantly. The same level of asymmetric induction was observed for ***R,R*-L11** with the Cl-substituent at the para position of the central phenol backbone. The ***R,R*-L10** ligand was definitely the most favorable in terms of reaction efficiency (95%), but with a slightly lower asymmetric induction (94% *ee*). Finally, ring size reduction in the amino alcohol moiety in the ***R,R*-L12** ligand was unsuccessful.

To demonstrate the wide applicability of the developed methodology, we have carried out the reaction of over sixty alkenes. While the SI material contains information about all experiments, Scheme 3 summarizes the most promising results obtained with the use of the dinuclear magnesium catalyst. Although we observed excellent yields and enantioselectivity for most substrates, the epoxidation efficiency varied depending on the chalcone structure, and particularly the location of the substituents on the benzene ring of substrates **P1**–**P11** as follows: *para*- (76–95%, 79–97% *ee*) > *meta*- (68–95%, 78–85% *ee*) > *ortho*- (0–32%, 18–55% *ee*).

In the case of chalcones containing *ortho* and *para*-methoxy substituents, only traces of the product were observed, while the substrate with the *o*-Me substituent turned to be unreactive.

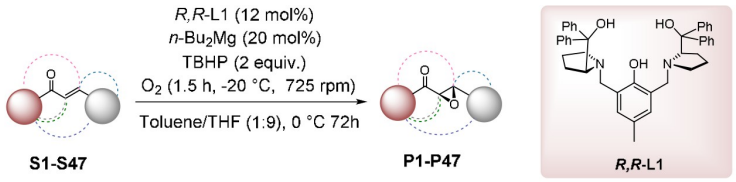
The study also revealed a significant decrease in selectivity for the 1-naphthyl substituent (**P12**: 38%, 52% *ee*), and an increase in selectivity for 2-naphthyl (**P13**: 86%, 96% *ee*). Such large differences may indicate the existing steric hindrance and difficulties in proper **S12** arrangement at the catalyst reaction center. It was also the very first time to obtain epoxidation products **P14** and **P15** (Scheme 3) with excellent selectivity > 97–99% *ee* and very good yields 83–86%. Additionally, excellent enantioselectivity (> 98–99% *ee*) were obtained for the substrates with the conjugated bond system for (2*E*, 4*E*)-1,5-diphenylpenta-2,4-dien-1-one (**S16**) and (2*E*, 4*E*)-1-phenylhexa-2,4-dien-1-one (**S17**), where the γ-σ double bond is in the acyclic system.

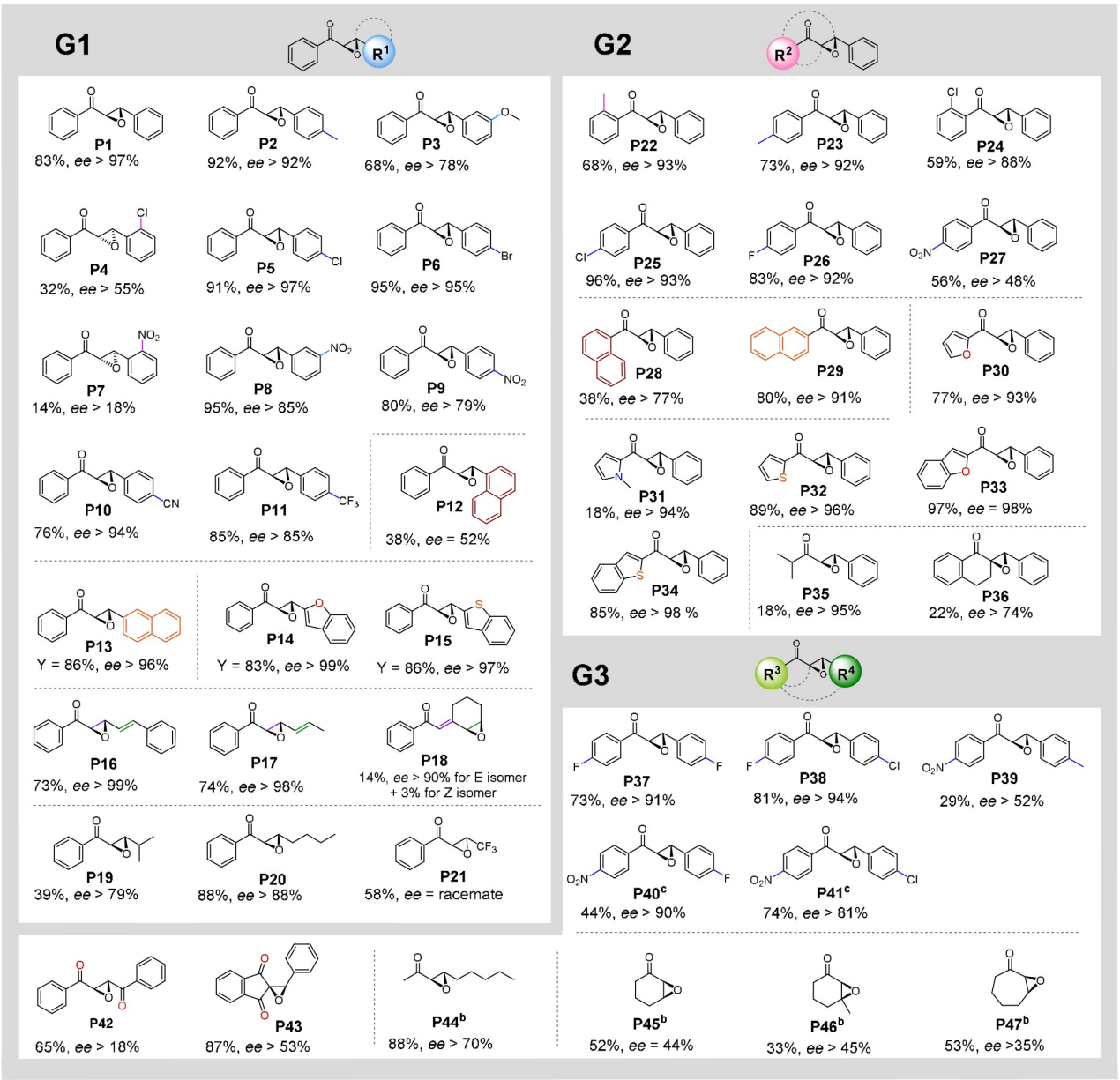
Epoxidation of **S16**, **S17** with condensed double bonds occurred at the α,β-position and resulted in the formation of the product with high yield and stereoselectivity. However, the epoxidation of **S18** (2-(cyclohex-2-en-1-ylidene)-1-phenylethanone), occurred on the external γ,δ-double bound albeit with only 14% yield probably due to sterically reason. At first glance, the substituents on the benzene ring in the chalcones **S22**–**S27** have a smaller effect on the enantioselectivity results (48–93% *ee*), however, a decrease in the yield for the products **P22**, **P24** with substituents in the ortho position (59–68%) can be noticed. A similar selectivity in **G2** group was obtained for the fused aromatic ring substituents as in the **G1** group. The selectivity of the **S28** epoxidation with the 1-naphthyl substituent reaches 77% *ee* (**P28**) compared to 52% *ee* for the **S12** counterpart, however the efficiency remains low at 38%, while for the **S29** substrate the results are very good and in practice match those for **S13**. The case of heterocyclic substituents is also much better. Epoxidation products were obtained for all five tested substrates **S30**–**S34**.

The enantioselectivity results are very high (93–98% *ee*) for the **P30**–**P34** products as well as good to high yields (77–97%). Interestingly, higher enantiomeric excess values were obtained for epoxidation of the **S35** substrate with a branched aliphatic substituent (18%, 95% *ee*) than for the structural isomer **S19**, but the reaction did not occur at all for substrate **S57** with longer aliphatic carbon chain on the carbonyl side. In the case of fluorinated substrates **S37** and **S38**, the enantiomeric excess and yield are at a very good level (73–81%, 91–94% *ee*), while *p*-NO_2- groups affected the overall yields and enantioselectivities (29–74%, 52–90% *ee*). Due to the poor solubility of the **S40** and **S41** substrates, in these specific cases, the epoxidation procedure was modified and instead of using 2.0 mL of the solvent mixture, these substrates were transferred to the reaction mixture as a suspension in 4.0 mL of dedicated solvent. It can also be seen that the *para*-NO_2-group on the ketone side adversely affects the selectivity of epoxidation if combined in addition to the presence of electron-donating substituents or the general absence of substituents on the benzene ring at the double bond, similar to the **P27** case (56%, 48% *ee*), for **P39** we have 52% *ee* and 29% yields. For the commercially available aliphatic linear enone **S44** the product was obtained with good enantioselectivity and good yield (88% > 70% *ee*) when the reaction was scaled up. The reactivity study of cyclic enones **S45**–**S47** resulted in obtaining products with moderate yields and enantioselectivity.

We also managed to recover the ***R,R*-L1** catalyst in 70–85% yield from the reaction mixture during product column chromatography by elution with a more polar eluent.

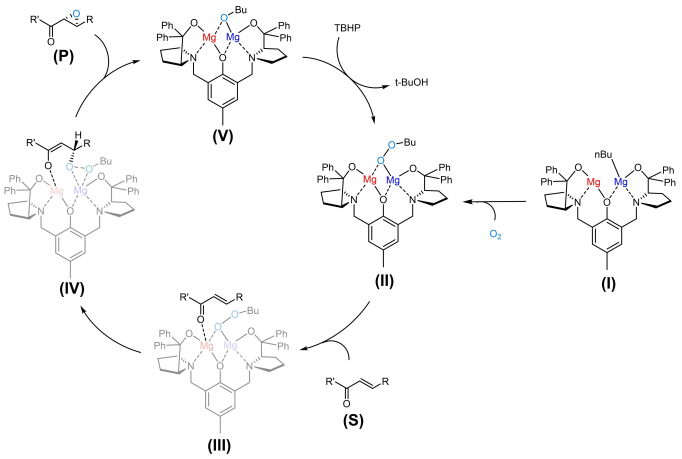
On the basis of the previously postulated mechanisms[21] and based on the absolute configuration of epoxides, we proposed a tentative catalytic cycle for enantioselective epoxidation of enones (**S**) mediated by chiral magnesium peroxide and TBHP (Scheme 4). It is important to notice, that based on our observation and previous experiments oxygenation step with O_2 is crucial for preformation of the catalyst (**II**) that is further regenerated with TBHP in catalytic cycle. We postulate that treating the chiral magnesium complex with O_2 leads to the inclusion of molecular oxygen between the magnesium-carbon bond of the Mg-*n*-Bu





[a]The reactions were carried out by stirring ligands 12 mol% *R,R*-L1 with 20 mol% *n*-Bu_2Mg (0.5 M solution in n-heptane) in a freshly prepared Toluene/THF (1:9) solvent mixture at room temperature for 1 h. After the synthesis of the chiral complex Mg-*R,R*-L1, the solution is cooled to -20 °C and the Schlenk vessel is connected to the line with a desiccant and further to the oxygen balloon. Oxygen is supplied for 1.5 hours at 725 rpm. Containing 2 eq. (0.8 mmol) of TBHP (4.0 M toluene solution), 1 eq. of substrate S (0.4 mmol), stirring at 0 °C for 72 h unless otherwise stated. [b]Reaction scale 0.12 to 0.16 mmol. [c]S40 and S41 were delivered to the reaction mixture as a suspension in 4.0 mL of dedicated solvent. [d]Isolated yields are given. fee was determined using HPLC analysis.

Scheme 3. Scope of the reaction.



Scheme 4. Proposed Catalytic Cycle.

moiety and this results in a catalytic formation of a reactive chiral peroxide (**II**, *n*-Bu at this stage), which is the proper catalyst. This chiral peroxide, also having a Lewis acid center, coordinates the carbonyl oxygen of the enone to give complex (**III**) followed by a nucleophilic oxygen attack from the *re*-face to the activated enone as described by the transition structure (**IV**), resulting in an epoxide (**P**) with the assigned configuration (for investigated enones mainly 2*R*,3*S*) and a chiral magnesium alkoxide (**V**) which completes the reaction cycle. The next step which the new cycle gets started is the regeneration of peroxide (**II**) from chiral magnesium alkoxide (**V**) using TBHP. Based on the previous study,[21] we can assume that regeneration of the catalysts (**V** into **II**) occurs with the formation of magnesium *tert*-butoxide species as the result of the alkoxide ligand exchange by TBHP. Overall, oxygen is needed to initiate the catalytic cycle by forming the proper catalyst (**II**), but its regeneration is possible with the TBHP oxidant only.

Conclusion

In conclusion, we have developed the most effective strategy to date to obtain enantiomerically pure epoxides derived from chalcones by using magnesium-based catalysis and readily available C_2-symmetry ProPhenol ligands. The catalytic system developed by us allowed to obtain a wide range of epoxides with high efficiency and very good enantioselectivity for both chalcones and more complex enones. By examining an extremely diverse group of electron-poor alkenes, we could also learn about the limitations of the proposed methodology. Chiral epoxides are versatile scaffolds and can be used for further functionalization, e.g., in the synthesis of biologically active compounds or pharmaceutical drugs. We believe that the results of our research on the asymmetric epoxidation of electron-poor alkenes will enable the rational development of new, efficient and environmentally harmless catalysts that can be successfully used in science and industry.

Experimental Section

General Procedure for Enantioselective Epoxidation of Substrates S1–S66

A 25 mL Schlenk vessel with a magnetic stir bar inside was heat-gun dried for 5 min under vacuum. (*R,R*)-ProPhenol ligand ***R,R*-L1** (0.12 eq.) was added to the Schlenk vessel and the system was placed under vacuum for additional 15 min. After the drying step, a freshly prepared mixture of dry solvents Toluene/THF (1:9) 1.84 mL was added to the vessel under an atmosphere of argon, followed by addition of (0.2 eq.) *n*-Bu_2Mg (0.5 M solution in *n*-heptane) and continued stirring at room temperature for 1 hour. After synthesis of the chiral complex, the solution is cooled to −20 °C and the Schlenk vessel is connected on one side to the vacuum/argon line and on the other side to the oxygen balloon *via* a glass connector. The vessel was briefly evacuated and backfilled with oxygen (repeated for three times). Oxygen is supplied for 1.5 hour at 725 rpm. Then 2 eq. (0.8 mmol) of TBHP (4.0 M toluene solution) followed by 2.0 mL of enone **S** (1.0 eq.; 0.4 mmol) solution were added in one portion under argon flow. After the addition of the enone **S** solution, the mixture is warmed to 0 °C and stirring is continued at this temperature for the 72 h. The reaction was quenched with the mixture (1:1; 4 mL) of saturated $NH_4Cl_{(aq)}$ and saturated $Na_2SO_{3(aq)}$ and stirred for additional 15 min. (650 rpm) or quenched with water (in case of enones S45–S48) without additional stirring. Quenched reaction mixture was transferred to the separatory funnel and washed with AcOEt (2 × 15.0 mL) or Et_2O (2 × 35.0–40.0 mL in case of enones S44–S48). The combined organic extracts were washed with H_2O (1 × 15 mL; in case of enones S45–S48 washed 2 × 50.0 mL H_2O) and brine (2 × 50.0 mL), dried over Na_2SO_4, and the solvent was removed under reduced pressure. After the removal of solvents, the crude mixture was subjected to silica column chromatography to yield the epoxide product **P**.

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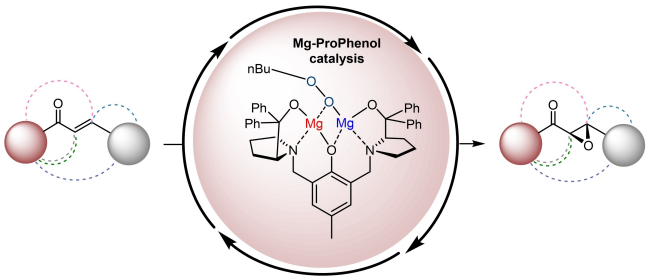
RESEARCH ARTICLE

Asymmetric Epoxidation of Enones Promoted by Dinuclear Magnesium Catalyst

Adv. Synth. Catal. **2021**, *363*, 1 – 10

J. A. Jaszczewska-Adamczak, J. Mlynarski*



- Readily available or easily to synthesis ProPhenol ligands
- The use of environmentally friendly non-toxic metal
- Mild reaction condition
- up to 66 substrate examples
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